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Tidally driven stick–slip motion in the mouth of Whillans Ice Stream, Antarctica

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ABSTRACT. We show that the ice plain in the mouth of Whillans Ice Stream (formerly Ice Stream B), Antarctica, moves by stick–slip motion. During a spring-tide period, rapid motions regularly occur near high tide and during falling tide. This correlation is weaker during a neap-tide period when the tidal magnitudes are less. Precise timing of these motion events suggests that they propagate through the region with a mean velocity of 88 m s^{-1}. We hypothesize that this speed is associated with the propagation of shear waves through a wet subglacial till. Motion events are also seen on more smoothly flowing floating ice. Event delays are very short between grounded and floating stations, suggesting the events propagate through the ice shelf as an elastic wave. We further hypothesize the events are caused by the interaction of a sticky bed, the accumulation of stored elastic strain through the compression of ice by upstream inflow, and tidal forcing. Motion events seem to be triggered either by reduction of vertical normal stresses at high tide or by the increase of shear stresses from sub-shelf ocean currents during falling tide. Event magnitudes are not related to the length of the preceding quiescent period, suggesting significant viscous dissipation within the till.

INTRODUCTION

Whillans Ice Stream (formerly Ice Stream B), Antarctica (Fig. 1), is the most studied ice stream in the world, but continues to surprise researchers. Scientific investigations on this ice stream began in 1957, when its downstream portion was crossed during the International Geophysical Year, well before the existence of ice streams was recognized. This area was later included in the Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS) during the 1970s, when this entire area was thought to be part of the floating Ross Ice Shelf. Since the discovery of ice streams, this ice stream has received intensive surface-based work, airborne surveys and satellite monitoring (see review by Whillans and others, 2001). Much of our current understanding of ice-stream mechanics results from these studies, including the discovery and sampling of the weak subglacial till that supports rapid ice-stream motion (Blankenship and others, 1987; Engelhardt and Kamb, 1998; Kamb, 2001) and the first recognition that ice-stream margins are the sites of major resistive forces determining ice-stream speed (Whillans and Van der Veen, 1997). Currently, this ice stream is decelerating (Bindschadler and Vornberger, 1998; Joughin and Tulaczyk, 2002), providing scientists with a magnificent natural experiment in ice-stream response behavior.

The mouth of Whillans Ice Stream contains a region called an "ice plain" (Fig. 1), where surface slopes are intermediate between those of active ice streams (order 10^{-2}) and ice shelves (order 10^{-1}), the ice thickness above buoyancy is only tens of meters, the basal shear stress is extremely low (order 1 kPa), and the bed is a till delta comprised of foresetted stratigraphy (Shabtaie and Bentley, 1987; Alley and others, 1989; Bindschadler, 1993). The heritage of field observations of the ice plain made it an obvious site to extend the measurements of deceleration and to examine their spatial variation, if any. A program designed to efficiently collect these data revealed the unexpected behavior of sudden, short-lived motions of the ice, interspersed with much longer periods of stagnation. This paper reports on this behavior and offers hypotheses to explain it.

Tides are known to affect the motion of tidewater glaciers (Meier and Post, 1987; Walters and Dunlap, 1987; O'Neel and others, 2001). The floating portions of these glaciers rise and fall with the tide, while their horizontal speeds decrease as the tide rises and increase as the tide falls. The opposite relationship between tides and horizontal motion was reported in Greenland on Jakobshavn Isbræ (O'Neel and others, 2001).

Tides also affect the vertical position of ice shelves, but it has only recently been reported that tides also affect the horizontal motion of both floating ice and adjacent grounded ice in Antarctica. Direct measurements have been made on Amery, Brunt and Ross Ice Shelves. Several sites on the Amery Ice Shelf exhibit unidirectional horizontal motion based on global positioning system (GPS) measurements (King and others, in press). However, GPS records from the Brunt Ice Shelf show that ice shelf experiences quasi-cyclonic horizontal motions that are related to the ocean tides or currents, with the maximum downstream velocity reached about 4 hours before high tide. These motions result in horizontal velocity reductions typically 50%, and even >100%, of the long-term velocity (Doake and others, 2002). Where it enters the Ross Ice Shelf, Ice Stream D exhibits a 50% variation in the downstream speed in anti-phase with the tide (Anandakrishnan and others, 2003). This variation is diminished 40 km upstream and is not seen 80 km upstream, although the site of this final observation may be poorly chosen to detect residual tidal influence on ice motion.

Previous to these studies, variations in vertical strain in basal water pressure at tidally synchronous periods observed 300 km upstream of the grounding line on Whi Ice Stream (Harrison and others, 1993; Engelhardt Kamb, 1997) and in the seismicity of the lower 86 km o nearly stagnant Ice Stream C (Anandakrishnan and A 1997). In this latter study, a flow relationship was inferred predicted higher flow rates at low tide (as later observe Ice Stream D).

Our report describes the most extreme exampl known tidal influence on horizontal ice motion. Du most of the tidal cycle much of the ice plain is compl stationary, only moving forward during brief perio high tide and at the midpoint of the falling tide. T short-period motion events are observed to propagate a the ice plain and onto the ice shelf.

DATA

The motion described in this paper was not anticipated. The data used were collected originally to better quantify the known multi-decadal deceleration of the Whillans Ice Stream ice plain (Bindschadler and Vornberger, 1998), and the collection strategy was designed for that purpose. To avoid the spatial interpolations and extrapolations necessary in previous velocity-change calculations, stations for the designed study were selected from sites occupied during either RIGGS, about 25 years earlier, or the Siple Coast Project (SCP), about 15 years earlier. Geodetic-quality Ashtech Z-12 GPS receivers were used with data stored internally and power supplied by deep-cycle marine batteries. Receivers were deployed by a one-man crew transported by Twin Otter using on-board GPS navigation to ensure accurate positioning of the receivers at former RIGGS and SCP sites. A minimum occupation time of 4 hours was imposed to determine an accurate site position. The minimum interval between surveys was set at 1 week. Based on the average velocity of the ice plain (400 m a^{-1}) and the anticipated $\pm$10 cm precision of the site coordinates, this plan ensured a velocity precision well under 1%, meeting the goal of precise velocity measurements at many locations determined over a relatively short period of time in a single season.

Twenty-nine stations were occupied twice during January 1999 (Fig. 1). Occupation times varied widely depending on aircraft logistics. Often receivers were left overnight or, in cases of inclement weather, for multiple days with data collection continuing until the external battery drained. Multiple receivers were deployed during a given flight, usually in the same vicinity, to minimize flight times between stations. Subsequent flights picked up and redeployed receivers. Data were downloaded to laptop computers during redeployment flight legs, and batteries were recharged overnight at Siple Dome, the base used during the survey. Figure 2 shows the temporal record of station occupations.

CONCLUSIONS

Stick–slip motion on the ice plain of Whillans Ice Stream is a surprising result. We conclude that the source events are caused by the tides influencing the stress field at the base of the lightly grounded ice plain in two ways. The need for two mechanisms is forced by our observation that, especially during spring tides, there are impulsive motion events at high tide and during the falling tide. At high tide, the mechanism we favor is the release of accumulated stress through the reduction of normal stress of the ice on the till. At falling tide, we propose that the sub-shelf tidal currents, which at this phase of the tidal flow are roughly parallel to the mean ice motion, increase the net basal stress sufficiently to release the ever-accumulating stress over the ice plain.

Slip events propagate from one station to another at a mean speed of 88 ± 79 m s^{-1}. This value is intermediate between the rapid elastic wave speed in ice (3830 m s^{-1}) and the slower 1.6 m s^{-1} deduced for the till underneath the stagnant Ice Stream C. Our value is close to the shear wave or Stokely-wave velocity and we suggest that these waves trigger the release of stored elastic strain as slip events across the ice plain. The displacement magnitudes are not correlated to the length of the preceding quiescent period, suggesting that some viscous dissipation may occur within the till. Our data did not allow the event-origin sites to be located with confidence, although the calculated directions toward the source events consistently point to regions where the ice plain has thickened since 1985.

The causal mechanics of these events may be similar to those underneath Ice Stream D and represent a characteristic of motion in the mouths of ice streams. On the other hand, we cannot reject the possibility that this peculiar motion is related to the observation of a sustained deceleration of the ice plain and the possible eventual stagnation of Whillans Ice Stream.